Laser Guiding at Relativistic Intensities and Wake-field Particle Acceleration in Plasma Channels

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Abstract. High quality electron beams with hundreds of picoCoulombs of charge in percent energy spread above 80 MeV were produced for the first time in high gradient laser wakefield accelerators by guiding the drive laser pulse.

Wakefield acceleration experiments to date have demonstrated that electrons can be accelerated by a plasma wave driven by the radiation pressure of an intense laser, with an electric field up to hundreds of GV/m[1, 2], indicating the potential for compact accelerators. Acceleration distance has been limited by the difficulty of maintaining laser intensity over long propagation distances in the plasma, resulting in a poor quality electron bunches with 100% energy spread and an exponentially small fraction of electrons at high energy[1].

We report the first guiding of relativistic laser intensities relevant to wakefield acceleration over many diffraction ranges (Z_R) by a plasma channel, and the resulting production of electron bunches of few percent energy spread, hundreds of picoCoulombs of charge, and milliradian divergence at energies above 80 MeV[3]. The high acceleration gradients of previous wakefield experiments are retained over longer distances, and the beam quality is comparable to state of the art RF accelerators. Experiments and supporting simulations indicate that the high quality bunches are formed from self trapped electrons when beam loading turns off self trapping after the loading of an initial bunch, and when the bunch is accelerated to the dephasing length over which trapped electrons outrun the wake.

Guiding at high intensities to produce a channel guided accelerator required controlling for both diffraction and plasma effects. Previous experiments demonstrated guiding for input pulse intensities at up to 2E17 W/cm^2[4, 5], where a parabolic transverse plasma density profile can be matched to guide the low intensity pulse. Relativistic self guiding occurs for intense pulses above a critical power P_c because the quiver motion of the electrons causes their mass to increase, changing the refractive index. This occurs in regimes of interest to wakefield acceleration and provides some self guiding, but is unstable [6]. The channel must hence balance both diffraction and instabilities at high intensity.

The multi arm l'OASIS Ti:Sapphire laser[7], operating at 800nm with chirped pulse amplification, was used to form the guiding channel using a variation of the ignitor heater method[5] and to drive the plasma wake (Figure 1 A). A plasma was formed by an ignitor pulse (15mJ, 60fs) in a supersonic H_2 gas jet with an atomic density of 3-4E19cm^{-3} and a constant density plateau ~1.8mm long. This plasma was heated by a ~50 mJ from a 150mJ, 250ps heater pulse. Hydrodynamic expansion of the plasma formed a channel[4]. The drive pulse (0-500mJ, 55fs) was focused into the channel at a spot of 7-8.5μm FWHM to reach intensities up to 1.1E19W/cm^2, resulting in Z_R~200μm so that the channel was ~ 10Z_R long. Laser propagation was monitored with a side interferometer, mode imager CCD, and transmitted light spectrometer. Electrons accelerated by the plasma wake of the drive beam were analyzed using an integrating current transformer (ICT), a phosphor screen, and a magnetic spectrometer.

By adjusting the timing of the beams, the channel profile has been adjusted to guide the drive pulse at various powers and to compensate for the presence of self guiding[8]. The plasma density profile of the channel (Figure 1B) shows a rise in density over the spot diameter~ 40% less than the low power matching condition, reflecting adjustment to compensate for self guiding at 4 TW (above P_c).

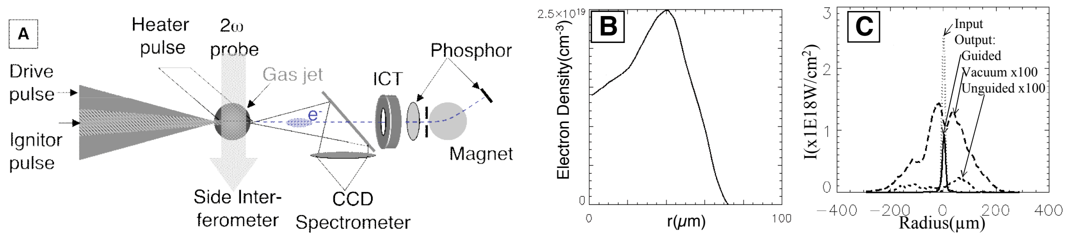

FIGURE 1. (a) Experimental setup showing the gas jet with laser beams and diagnostics. (B) The density profile of the channel obtained by Abel inversion of the side interferogram. (C) Mode of the beam at 4TW, showing enhanced transmission with the guide on (unguided modes multiplied by 100 to appear on the same scale). The guided and input modes are similar.

The channel guides pulses up to 4 TW (7μm input spot, 7E18 W/cm^2) without aberration, as shown in figure 1C. With the channel on, the output spot matches the input. Guided intensity is inferred to be near 2.5E18 W/cm^2. Propagation of the main beam in the channel also did not change the side interferometer image, indicating that the laser was well confined to the channel, as leakage outside the channel would ionize additional gas. The transmitted laser spectrum was also consistent with confinement. The vacuum output displays diffraction, indicating the effectiveness of the guide. With the gas jet on but the channel off, diffraction is increased by ionization effects, showing that self guiding alone is insufficient to efficiently guide the beam. This was confirmed by the interferometer.

Transmission at 4 TW was 1/3 less than at low power, indicating power was deposited in plasma waves. This is consistent with simulations (below), which indicated that a plasma wave averaging ~200 GV/m was excited in the last 0.5 mm of the guide. No electrons were self trapped, making controlled injection experiments possible. Colliding pulse injection[9] experiments are under way in this geometry, and controlled injection may provide more stable higher quality beams than self trapping.

Electrons were trapped and accelerated at 9 TW, confirming the presence of a large plasma wave. Optimal performance was found in a channel with an axial density of 1.9E19cm^{-3} and a profile with 40% less rise in density over a spot diameter than the low power matching[3]. The laser was well confined to the channel at this power but some aberration was always present, with output mode sizes near 24 μm FWHM, likely due to strong self guiding. The drive laser pulse was a factor of two longer than the linear plasma period, i.e. in the self-modulated regime [6]. This regime allowed comparison to unchannelled experiments, and allowed trapping of background plasma electrons, yielding high charge electron beams without a separate injector.

The channel guided accelerator produced high charge electron beams with low energy spread at high energy, and with low divergence[3]. Figure 3a shows a bunch of 3E9 electrons within an energy spread of ±4% centered at 78MeV and with divergence ~3mrad. Due to pointing fluctuations which change the incoupling of the drive beam to the guide, this feature varied shot to shot, and bunches energy spread as low as 2% with 2E9 electrons at 86 MeV were observed, as well as bunches of >1E9 electrons at energies up to 150MeV. Total charge in the electron beam was near 2E10 electrons; the low energy portion can be separated using a bend magnet, leaving a high energy high quality bunch. The normalized geometric emittance obtained from assuming the bunch comes from a source ~ the laser spot size is 1-2 π-mm-mrad, competitive with state of the art radiofrequency facilities.

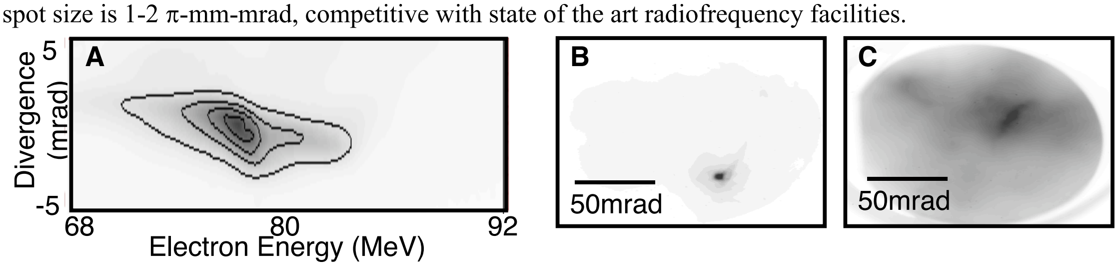

FIGURE 3. Electron bunches. The electron energy spectrum of the channeled accelerator (a) shows the appearance of monoenergetic features, here with 3E9 electrons in a bunch with energy spread of 4% FWHM at 78 MeV. Divergence was near 3 mrad FWHM for this bunch (a), and 6 mrad for the whole beam (b). The unguided accelerator in the same gas jet by contrast shows a nearly smooth exponenetial spectrum with a few MeV temperature (not shown), and much wider divergence (c).

Two dimensional particle in cell simulations performed with parameters close to the experiment using the code VORPAL[10] show formation of bunches similar to those observed in the channeledaccelerator. Loading of the wake by the initial electron bunch trapped suppressed further injection. This lead to a bunch of electrons isolated in phase space (Figure 4 a). If this bunch was accelerated until it dephased from the wake, the leading edge of the bunch was decelerated while the tail was still accelerating, concentrating the particles in energy and forming a low energy spread bunch at the dephasing length (Figure 4B). Matching accelerator length to the dephasing length for the jet length and Z_R used required a guiding channel. This can alternately be done with a short jet or long Z_R, though these methods are less efficient than channeling (below).

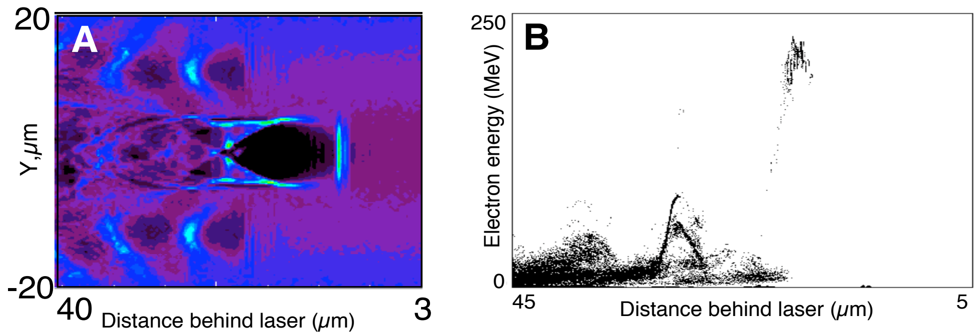

FIGURE 4. Simulations show that beam loading and pulse evolution turn off injection after the trapping of an initial bunch, resulting in a bunch isolated in phase space. This is visible in the density contour (A), where the wake amplitude is lowered following the bunch in the first bucket. The particles are then concentrated in energy at the dephasing length (B).

To evaluate the impact of dephasing on the accelerator experimentally, jets of variable length and density were used without channeling[11]. The highest energies for a given density, as well as the most monoenergetic features present in phosphor images were obtained when the beam was extracted at the dephasing length, confirming the importance of tuning the accelerator to the dephasing length. The beams were less stable and lower quality than in the channeled accelerator, indicating the advantage of controlling and extending laser propagation length using the channel. No difference was observed between operation in a neutral gas jet and a pre-ionized (but not channeled) plasma, indicating that channeling and not ionization was the important effect. Monoenergetic beams have also been observed using large laser spots to extend Z_R[12, 13], but this method produced lower charge and energy per laser power than channeled experiments since laser intensity was reduced by the large spot size.

In conclusion, experiments have demonstrated guiding of relativistically intense laser pulses over many Z_R in plasmas [8]. Using the channel to match accelerator length to the dephasing length produced high quality electron bunches with low energy spread. This offers the possibility of new classes of experiments on laser driven accelerators and indicates that development of high energy high quality beams is feasible using this method, benefiting many applications.

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